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# Operating results of the FlexiFuel-SOFC system with gasified biomass using CFY-stack module

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## Abstract

The stationary SOFC system utilizing gas from a novel biomass updraft gasifier with gas burner is under development within the European Union Horizon2020 project “FlexiFuel-SOFC” No. 641229 by Windhager, BIOS, HyGear, AVL, Fraunhofer IKTS, Wuppertal Institute, TU Delft and Utrecht University. The system is based on MK352 CFY-stacks with Chromium based (CFY) interconnects and electrolyte supported cells. These stacks are robust, redox stable and demonstrated low degradation rates. The stacks were arranged to modules of eight 30-cell stacks and were electrically connected in series. The stack module was pre-tested at the test rig at IKTS and showed performance in accordance with system requirements. Stationary power points were measured to compare the behavior of the stack module with system tests at AVL and BIOS. For an optimized start of the system a procedure for a start of the stack module with $CH_4$ containing reformate was determined. After shipping the stack module to BIOS in Graz it was tested in the system environment and showed comparable results. BIOS as the system operator was responsible for the operation of the gasifier and gas cleaning unit. The SOFC system developed and operated by AVL reached stable part load operating conditions with a power output of >6 $kW_{el}$. The SOFC system was operated with real biomass product gas for several days. Tar was thermally cracked and steam reformed prior to SOFC anode inlet. Particles, chlorine and sulphur were removed by the gas cleaning unit. The operating results of the stack module at lab conditions and at the real system are in a good agreement. The SOFC stack module performance in terms of cell voltages, stack temperature distribution and fuel utilization under biomass reformate fuel will be shown and reasons for observed differences in stack module behavior discussed.

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# Introduction

Efficient technologies are a key for the future energy sector. $CO_2$ neutral fuels like biomass are locally available and should preferably be utilized in decentralized heat controlled applications due to transport and logistic reasons. Combined heat and power (CHP) technologies in the small power range are rare and due to their restrictions regarding electric efficiency and fuel flexibility, their market penetration is still poor [1, 2, 3, 4, 5]. Against this background, the Horizon 2020 project FlexiFuel-SOFC (Grant Agreement No. 641229, 05/2015-04/2019) aims at the development of a new, highly efficient and fuel-flexible micro-scale biomass CHP technology consisting of a small-scale fixed-bed updraft gasifier coupled with a gas burner, a compact gas cleaning unit (GCU) and a solid oxide fuel cell (SOFC). Within the project, the technology is developed for a capacity range of 25 to 150 kW (fuel power related to the NCV of the fuel) and thus shall be suitable for decentralized CHP applications.

Within previous projects the partners Windhager and BIOS developed a small-scale updraft fixed-bed gasifier technology known as the PuroWIN in the nominal fuel power range between 24 and 60 $kW_{th}$, with very low dust emissions [4]. Within the project this gasifier is further developed to enhance fuel flexibility and for the integration into a SOFC-based CHP system. Thereby, the further enlargement of the fuel spectrum applicable from softwood pellets and wood chips to short rotation coppice and selected agricultural fuels such as olive stones, nut shells and agro-pellets plays a central role.

Moreover, a compact gas cleaning concept covering particle precipitation, removal of HCl, $H_2S$ and other sulphur compounds and tar cracking is developed by TU Delft and HyGear. The aim is to provide a product gas with no PM, $H_2S$ contents <1 ppm, HCl contents <5 ppm and to upgrade the tar rich product gas by cracking specific tar compounds which cannot be converted by reforming in the fuel cell system.

Last but not least, a SOFC technology enabling operation at nearly atmospheric pressure in a defined temperature range of the product gas (700 to 800 °C), a high power density of the SOFC stacks and a high electric efficiency (stack efficiency of about 40 % with product gas from the updraft gasifier) was developed.

The used CFY stacks developed by Fraunhofer IKTS were assembled to stack modules and transferred to AVL which developed the SOFC system for system integration.

Gasifier, GCU and SOFC were connected to an automatically operated CHP system. It is the objective to finally run the CHP system without any need for auxiliary heating sources during plant start-up and continuous operation and therefore, energy from the SOFC off-gas is used for internal heating purposes. Remaining waste heat is recovered in a highly efficient heat exchanger system to provide heat for space heating and warm water supply.

This new CHP technology shall enable an almost equal-zero emission (regarding CO, OGC, NOx, HCl, $SO_x$, PAH and PM and due to the utilization of biomass also regarding $CO_2$) fuel-flexible heat and power generation with an overall efficiency close to 90 %.

Accompanying risk assessments, safety analyses, techno-economic and environmental impact assessments and market studies shall assure that the new technology resulting from the project is market competitive. These assessment-related tasks are covered by Utrecht University, Wuppertal Institute and BIOS.

# 1. Scientific Approach

Micro-scale CHP systems are mainly based on fossil fuels such as natural gas and heating oil fired applications for block heating, Stirling engines and steam expansion machines. Attempts to couple these technologies with biomass combustion processes have in most cases not led to marketable products so far and electric efficiencies of such applications are rather low (8 to 14 % related to the biomass input power) [2, 5]. An alternative option to combustion based CHP technologies are gasification based micro-scale CHP technologies. Such systems have already been introduced into the market. They are usually based on downdraft or multi-stage gasification systems coupled with gas cleaning units and gas combustion engines. They exhibit higher electric efficiencies (~25 %) but limited overall efficiencies (65-75 %) due to intermediate gas cooling steps. Other disadvantages are the high fuel quality requirements, high efforts for gas cleaning and rather complex process schemes [1, 2, 3].
To overcome these problems and to develop a highly efficient and fuel-flexible micro-scale biomass CHP technology a new approach has been chosen. The technology is based on a fixed-bed updraft gasifier coupled with a two stage gas burner and a hot water boiler [29]. A part of the product gas is extracted from above the fuel bed and supplied to a high temperature gas cleaning unit (GCU) through a side stream while the remaining product gas is burned in the gas burner and utilised for heat supply in a hot water boiler. The cleaned product gas then passes through the SOFC system for electricity production. Hot off-gases from the SOFC system are partly used to heat the GCU and then supplied to a heat recovery system (second boiler compartment). Suction fans downstream of the boiler and the heat recovery system are used to overcome the pressure losses of the single units, thus the plant is operated at underpressure.
The operation of the GCU and the SOFC system in a side stream of the gasifier brings thereby significant advantages compared to an utilization of the full product gas stream in the SOFC system. Since small-scale CHP systems are usually operated in a heat-controlled mode a limited partial load operation capability of the whole system would result if the entire product gas would be utilised with the SOFC system. A process flow chart and a picture of the first testing plant realised are shown in Figure 1.

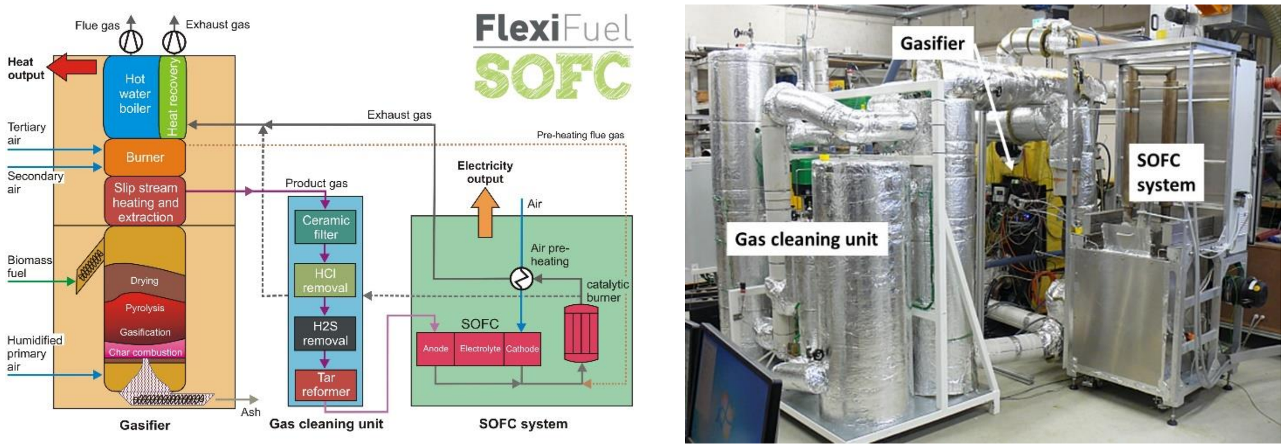


Figure 1: Basic scheme of the novel micro-scale biomass CHP technology (left) and a assembled testing plant with connecting tubes instead of stack module for initialization tests of the gasifier and the high temperature GCU (right).

The partial load operation capability of the gasifier is very good and allows for operation down to less than 30% of its nominal power. By using a side stream of the product gas, the SOFC can run at full load even at low heating demand of the heat consumer. As soon as the heat demand increases, the gasifier load is also increased. This leads to an optimised number of full load operation hours of the SOFC system. Thereby, high overall electricity production per year can be achieved and, due to the smaller SOFC system, the benefit from the electricity production is optimised and the payback time reduced.
A heat-only operation (in case of unexpected shutdowns due to failures in the GCU and the SOFC system) or very low load demands can be realized without additional components. This system configuration also allows a start-up procedure without the need for auxiliary (electric) energy for pre-heating the GCU and the SOFC system since during start-up this energy is provided from flue gas gained from the product gas combustion in the gas burner. Moreover, the number of complicated start-up and shut down processes can significantly be reduced due to the high load flexibility of the gasifier.

## 2. Experiments/Calculations/Simulations

System simulations were applied to develop the detailed plant concept to gain mass and energy balance data. First estimations were validated by separate experiments, i.e. gas composition measurements during utilization of various biomass fuels in a fixed-bed updraft gasifier coupled with a gas burner and a boiler as well as performance map tests with a MK352 CFY-stack. After some details regarding the stacks and operation points the assembly to stack modules and system operation will be explained below.

<u>MK352 stack design</u>
The MK352-stacks have well matched materials like CFY and 10Sc1CeSZ with the latest stack component technology in the field of cells and glass seals (Figure 2). The cross flow design with internal gas and open air manifolds offers the possibility of designing compact stacks and systems [7, 8, 9, 10, 12, 13, 14]. It allows an easy gas sealing at the end plates and a uniform air distribution over all cells by external manifolds. The explosion view of the stack in Figure 2 shows the low amount of single parts and their easy assembly to a stack. The stacks were proven in SOFC operation for more than 20,000 h with an overall degradation rate of $\Delta P/P_0$=0.7 %/1,000 h ($\Delta$ASR=20 m$\Omega$cm²/1000 h), more than 120 thermal cycles without flushing gas with $\Delta P/P_0$=0.5 %/10 cycles [7, 11, 13, 15] and are commercially available.

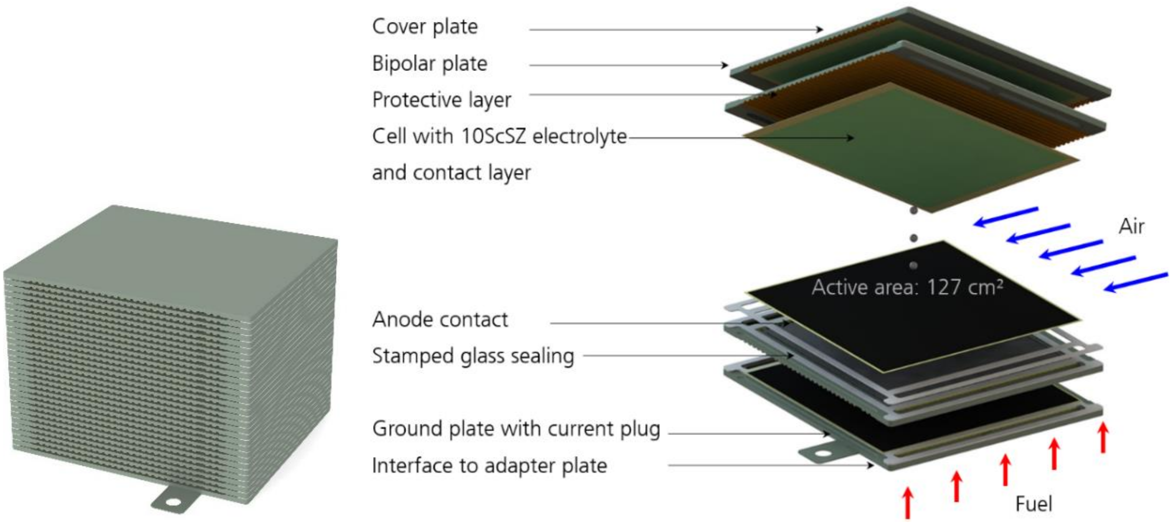


Figure 2: MK352 stack design 30-cell stack (left) and explosion view (right)

The sealing with semi-crystallizing glass with adjusted thermal expansion leads to a tight stack which can be handled at room temperature without any compression. Two layers of glass sealing elements, directly stamped out from the tape casted foil, assembled on both sides of the interconnect, eliminate the necessity of an additional lamination step and allow better quality at the abutting edges. The electrolyte supported cell has an active area of 110x115 mm² (127 cm²) and utilizes proprietary IKTSG3 electrodes developed at IKTS. After a quality check of every component and assembly, the stacks are sealed, initialized and ready for integration into single stack test rigs for performance evaluation or assembled to stack modules.

<u>MK352 stack performance map</u>

A performance map is defined as a set of stationary operation points at different rated power output and is the best way to characterize a stack because every point will be reachable by comparable boundary conditions, whereas an I-V-curve is mostly time dependent due to transient effects like self-heating. The hotbox or simulated hotbox tests take place at a test rig with mass flow controllers and preheated gases at defined operation state. The operation with preheated gases shows a system relevant temperature profile in the stack, monitors real operation parameters and is a common way to predict characteristics of stacks for system operation. The reference temperature is measured with a radiation shielded thermocouple type K 10 mm outside the stack air outlet and is adjusted by air inlet temperature.

Based on performance tests with a 30 cell stack operated with simulated wood gas reformate from the gasifier (for gas composition see Table 1) at 35 A, $\eta_{FU}$=75 % and 835 °C a power output of 807 W was measured. Over a wide parameter range the performance map has only minor changes in power output, which makes the CFY technology so unique [12, 15]. For the aimed 6 $kW_{el}$ a stack module with eight 30 cell stacks is necessary.

The SOFC input gas has high $CO_2$ and steam contents resulting in a decreased power output. Raising the $CH_4$ content shows a shift of temperatures caused by internal reforming at the active area of the cell with minor changes of the power output [15]. This brings the advantage that less air flow is necessary for system operation which leads to less power demand for the balance of plant components. Fine tuning of $CO_2$, $H_2O$ and $CH_4$ concentrations will increase the performance of the stack module, but is not in focus at this point of development.

Stack module assembly

The arrangement of 8x30 cell stacks is based on former stack module development [14]. Improvements and adjustments were added to get an optimized stack module for the application with product gas from biomass gasification (Figure 3). All stacks are connected in series to get a valuable high voltage output. This makes a high voltage isolation to the surroundings of the stacks and the adapter plate necessary. The adapter plate consists of brazed laser cut sheet metals with an isolation layer. All gas connections are on the bottom side for an easy system coupling and good insulation. Air flows from the middle to the right and left stack-tower and is collected at each side to a single outlet. Fuel-gas-in is divided in the adapter plate to the left and the right tower and collected at the outlet.

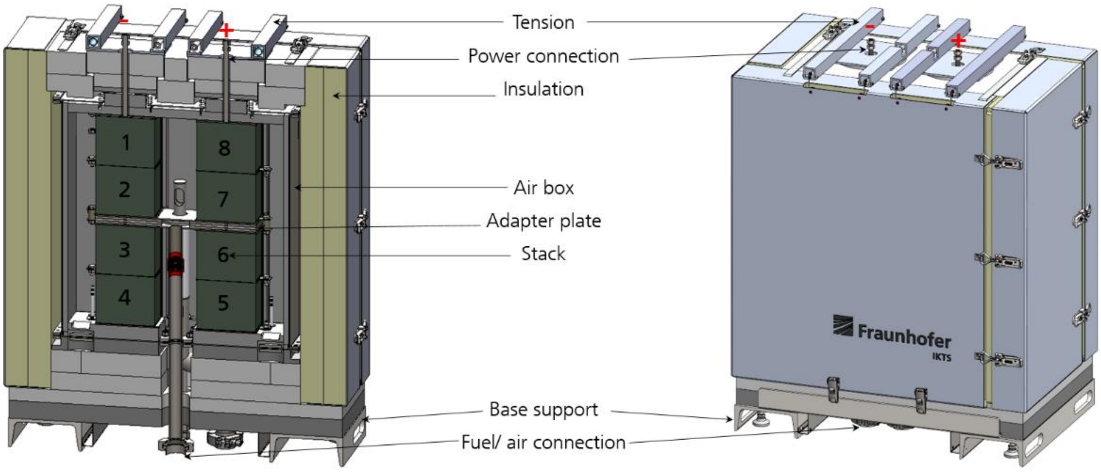


Figure 3: 3D model of 8x30 cell stack module

The base plate supports the stack module was made from insulation material with high mechanical stability to transfer the force from the two compression systems in the cold region to the two stack towers with high insulation against heat transfer. Voltage sensing of every stack, several thermocouples (TC) and pressure sensors characterize operating conditions (see Figure 4).

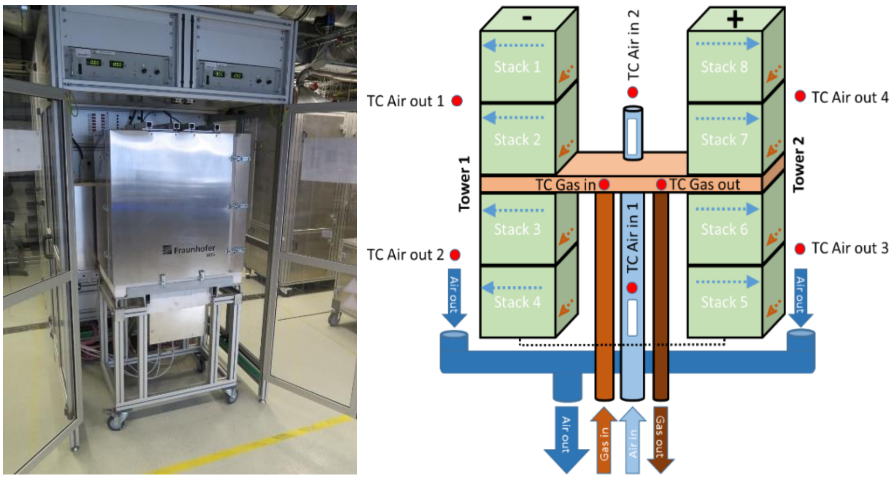


Figure 4: Right: Stack module integrated in test rig at Fraunhofer IKTS for acceptance test; left: schematic view to monitor the place and name of thermocouples

The stack module was first tested at Fraunhofer IKTS with a customized test rig “FuelCon Evaluator S” with mass flow controllers and then after approval shipped to AVL/BIOS. After successful tests with a dummy stack module for checking system operation, the complete CHP system was operated.

System assembly

The requirements for the SOFC system were determined by simulation and aligned with the process development to establish the relevant process parameters for the subsequent component development comprising stack module, air heat exchanger, afterburner, suction blower and exhaust gas cooler.

An adequate humidification of the product gas enables a constant gas quality at varying fuel compositions. For reaching high efficiencies tar cracking is necessary. Therefore, a first high temperature tar cracking stage developed by BIOS has been integrated in the product gas extraction concept of the gasifier. After dust / soot, HCl and S-compound removal in the gas cleaning a second reformer cracks long chain hydrocarbons.

The interface port connections between the stack module and the SOFC system are designed as short as possible but enable a separate testing of the system with bypass pipes and a separate test of a stack module at a test rig.

Figure 5 shows the SOFC system with the stack module at the top. The gas processing part (air heat exchanger, afterburner, air filter, throttles, venturi pipes) is mounted below. The cell voltage monitoring device as well as the electric cabinet are positioned at the backside.

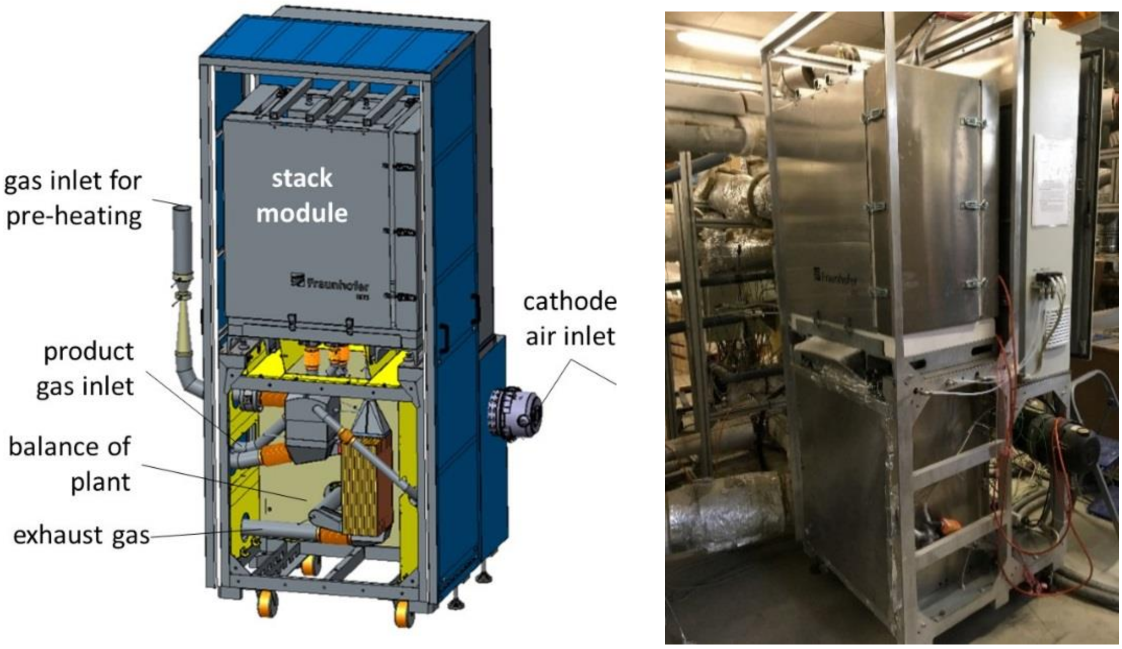


Figure 5: CAD drawing of the SOFC subsystem (left), Picture of the SOFC subsystem at plant operation

An underpressure operation on the air side was required to enable the coupling with the biomass gasifier, which runs at almost atmospheric pressure. Therefore, the cathode air blower, typically positioned at the air inlet of the SOFC system, was relocated to the exhaust gas outlet to operate as a suction blower. This leads to less deformation of the high temperature SOFC air box and therefore less internal air by-pass losses, which ultimately improves the stack module performance. For the evaluation of different suction blowers a separate blower box was positioned nearby the SOFC system and includes also the exhaust gas cooler and the e-load.

System BoP components

The plant uses one main suction blower, which draws fresh air as well as reformed product gas through the SOFC system. The fresh air is pre-heated before entering the SOFC cathode. In parallel, the product gas side stream is drawn from the gasifier. The product gas side stream is firstly conditioned in the GCU, before entering the SOFC anode for further electrochemical conversion and generation of electrical power. The anode off gas is mixed together with the cathode off gas in the afterburner to produce heat (hot exhaust gas) for the air pre-heating and the heating of the gas cleaning unit. The hot exhaust gas is then collected and connected to the heat recovery unit, which is integrated in the boiler located downstream the gasifier and the gas burner.

To be able to operate the gasifier and the SOFC separately, both systems have individual control systems which communicate with each other. The gas cleaning unit collects all data from the sensors and transmits them directly to the SOFC control system. Therefore, the gas cleaning unit is controlled directly by the SOFC control system. The control systems of the gasifier and the SOFC share status signals so that each sub-system is aware about the operating state of the other systems. Additionally, the sensor data of the gasifier are transmitted to the SOFC control system where all data are logged.

To evaluate the gas composition at the SOFC inlet several measurement campaigns comprising FT-IR measurements (Gasmet DX 4000), gas sampling with gas bags and subsequent analyses by GC MS, high temperature dust measurements and tar measurements according to the tar protocol have been performed. A venturi pipe is used to measure the product gas flow between the GCU with reformer and the SOFC.

## 3. Results

Stable operation points of the gasifier with integrated tar cracking and cleaning of the gas were reached and are described in [6]. During operation of the gasifier with wood chips, the product gas composition shown in Table 1 was measured. It matches well with the calculated composition gained from system simulations, however, the contents of combustibles are slightly higher.

Table 1: SOFC inlet gas composition for operation with wood chips calculated by simulation for first stage design versus measured values at test rig and system operation

| | CO | $H_2$ | $H_2O$ | $CO_2$ | $CH_4$ | $N_2$ | $V_{gas}$ @ 35 A in Nl/min |
|---|---|---|---|---|---|---|---|
| Calculated | 11.4 % | 29.2 % | 25.5 % | 13.1 % | 0.0 % | 20.8 % | |
| Test Rig @ IKTS | 11.4 % | 29.3 % | 25.5 % | 13.0 % | 0.0 % | 20.8 % | 192 |
| System operation | 12.9 % | 30.3 % | 22.9 % | 17.2 % | 0.6 % | 16.0 % | 164 |

At the acceptance test of the stack module at the test rig the calculated gas composition was applied with minor differences. All single stacks show nearly the same performance when they operate at the stack module compared with the power output recorded during single stack initialization. Leakages can be detected by the voltage during operation without current (OCV) when utilising gas mixtures with no water or $CO_2$ because the OCV is very sensitive towards the oxygen content. OCV values calculated by the prognosis tool "SimTool" at temperatures of 700-830°C give predictions for the range of the OCV. A gas tight 30 cell stack in 40 % $H_2$ and 60 % $N_2$ (40/60/0) gas composition reaches an OCV of >37.5 V (see Figure 6). Leakages dilute the gas with oxygen and are well detectable. The temperature dependence is much lower than the impact of oxygen.

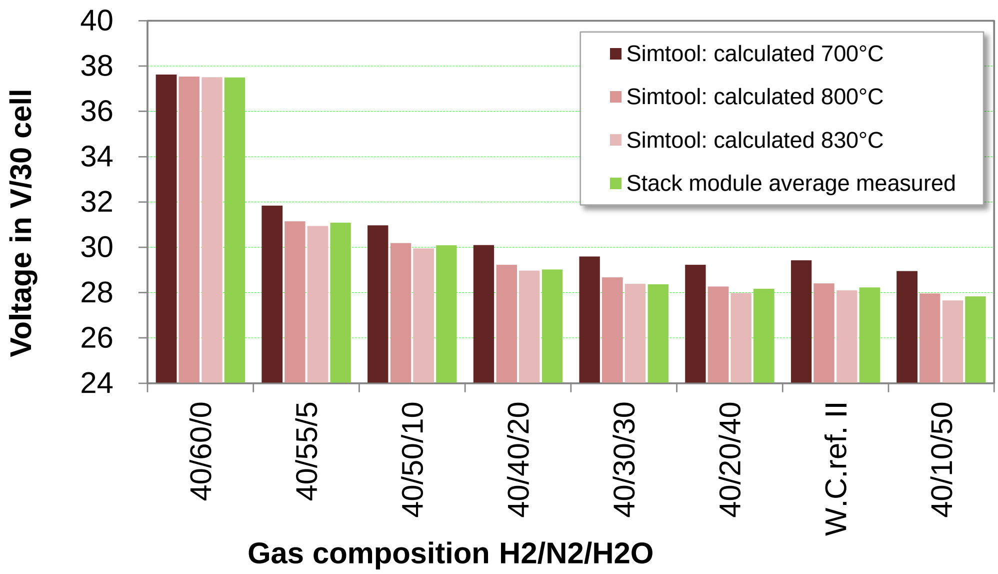


Figure 6: OCV of different gas composition calculated and measured at 820-830°C (green) with 30 cell stacks integrated in a stack module at 700°C to 830°C

At a steam content of >5 % the OCVs are homogenized and show the same values in the stack module. Small leakages are not detectable under these conditions. This effect can be used to get a rough estimation of the oxygen content in the gas faster than gas analysis by additional equipment. By monitoring single stack OCVs, the steam or $CO_2$ content can be estimated (sensed by the stack), which allows a quick check of the gas quality and the operation of the gasifier and the GCU. The OCV dependence on the steam content in the range between 5 and 50 % is shown in Figure 6. A perfect agreement between calculated and measured values is achieved. The value for wood chip reformate shows that the influence of $CO_2$ is comparable to the one of water (total concentration of steam + $CO_2$ =39 %). The small deviations of the measured OCV data for wood chip reformate are due to a lower temperature of 820°C.

After promising that the stack can be a good sensor it will be shown that it is an efficient energy converter too. The stack module was validated with simulated wood chip reformate at 35 A, 75 % fuel utilization and shows a power output of 6430 W (Figure 7). Changes in fuel utilization lead to uniform power output changes of the stacks and have only minor impact on the overall power output ($\eta_{FU}$ +5% → ΔP -48 W).

The performance map of a single 30 cell stack at comparable conditions gives 807 W and confirms a good integration of the single stacks in the stack module as well as a wide operation window range and robustness of single CFY-stacks. All eight stacks range from 799 W to 813 W and a low power scattering of +/-7 W is achieved for the single stacks.

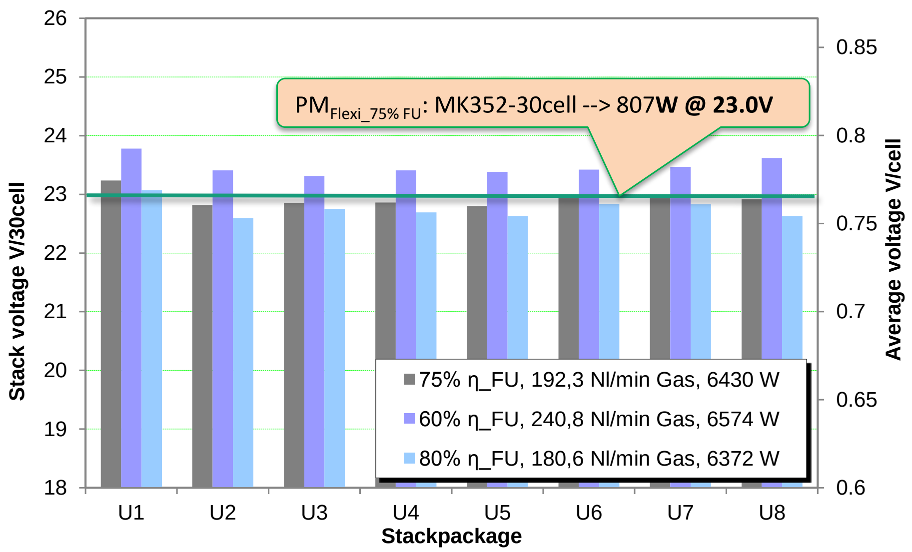


Figure 7: 8x30-cell MK352 stack module performance at 35 A with simulated wood chip reformate for different gas utilization at IKTS test rig

By reducing the air flow from 700 Nl/min (42.000 Nl/h) to 500 Nl/min (30.000 Nl/h) only a small difference of the power output is visible which is due to temperature profiles over the cells. The module can be operated in a wide air flow operation window with respect to the linear behaviour of the generated pressure drop. Figure 8 shows a comparable pressure drop at overpressure operation (test rig at IKTS) and underpressure operation with the suction blower (system). This verifies that the air box (Figure 3) is stable enough to withstand the overpressure without air bypass. It is possible to have a cross check for air flow by monitoring pressure drop at given temperatures as an easy-to-control value „sensed by the stack".

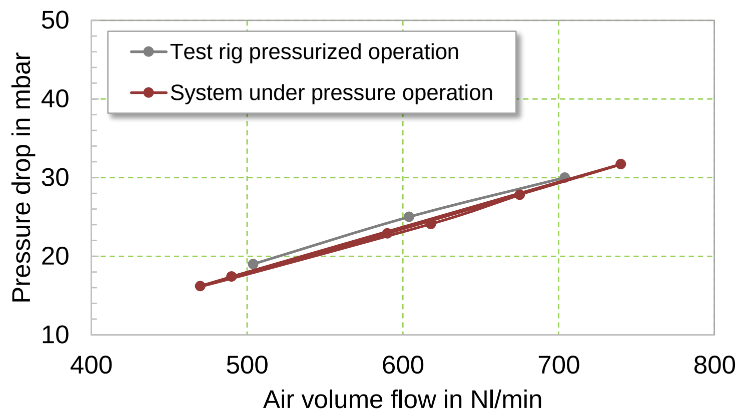


Figure 8: Pressure drop of 8x30-cell MK352 stack module performance at 35 A with wood chip reformate at different air flows in test rig and system operation at 830°C

At higher current load the stack module provides up to 8410 W (see Figure 9). Also lower power loads are possible for operation at partial load. This gives a wide operation window in terms of generated power output.

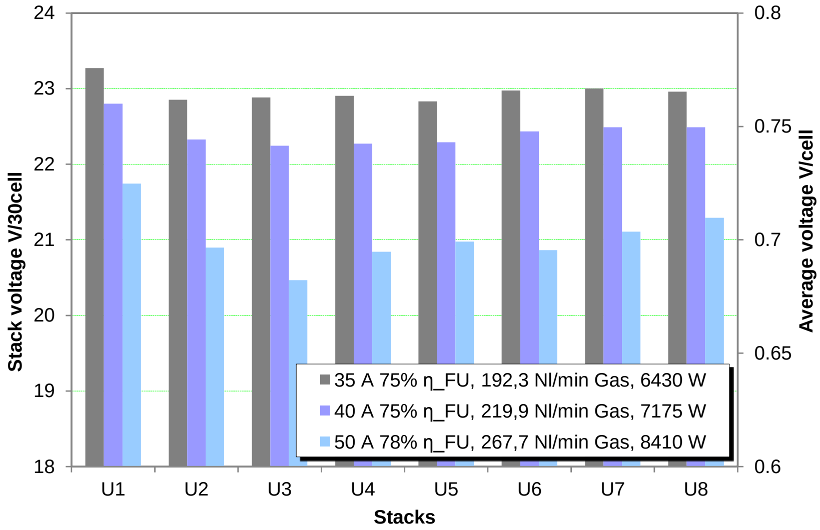


Figure 9: Voltage of 8x30-cell MK352 stack module performance with woodchip reformate at different currents at 835°C with 700 Nl/min air

The tests of stationary operating points were followed by several start-stop cycles and load variations and give a good input for system design. At a system level a positive synergy for the start procedure is the use of hot exhaust gas from the gas burner downstream the gasifier to pre-heat the SOFC during start-up, eliminating the need for an additional start-up burner as well as reducing system complexity and control requirements.
The shipment of the stack module as well as the integration were successfully solved in the past [14, 16] and are becoming a routine process. The SOFC system operation tailored to the gas composition of the cleaned and reformed product gas from the gasifier was however new and some obstacles had to be overcome.
A stable initial operation was reached and showed promising results (see brown columns in Figure 10). Grey columns are values from standard operation at the test rig at IKTS for comparison (see also Figure 7-9). Stack 1 (U1) has a poor performance which can be attributed to a possible leakage on the top of the stack module but is still performant enough for operation. For stack 3, 5 and 6 (U3, U5, U6) no single voltage measurements were available, the values are estimated from the mean voltage without ohmic losses from the current plugs (estimated from other tests). The stacks 2, 4, 7 and 8 behave quite uniform but show a lower voltage than during the acceptance test. By linear interpolation of power vs. fuel utilization (power decrease) as well as temperature (power increase) the low values cannot be explained. The system was operated with low air flow (50 % oxygen utilization at 35 A) which has no impact on the power output and needs less power for the suction blower. The two temperature profiles on the right side at Figure 10 show a 16 K to 38 K higher temperature of the stacks at system operation, slightly higher air inlet temperatures and 46 K lower gas inlet temperatures. The gas inlet temperature has only a minor impact on the stack temperatures because of the low volume flow. The air determines mainly the temperature profile over the stack. The opposing trend of low air flow as well as higher air inlet temperatures from test rig operation to system operation is not fully understood, but can be affected by the integration as well as the heat loss in the different operation modes.

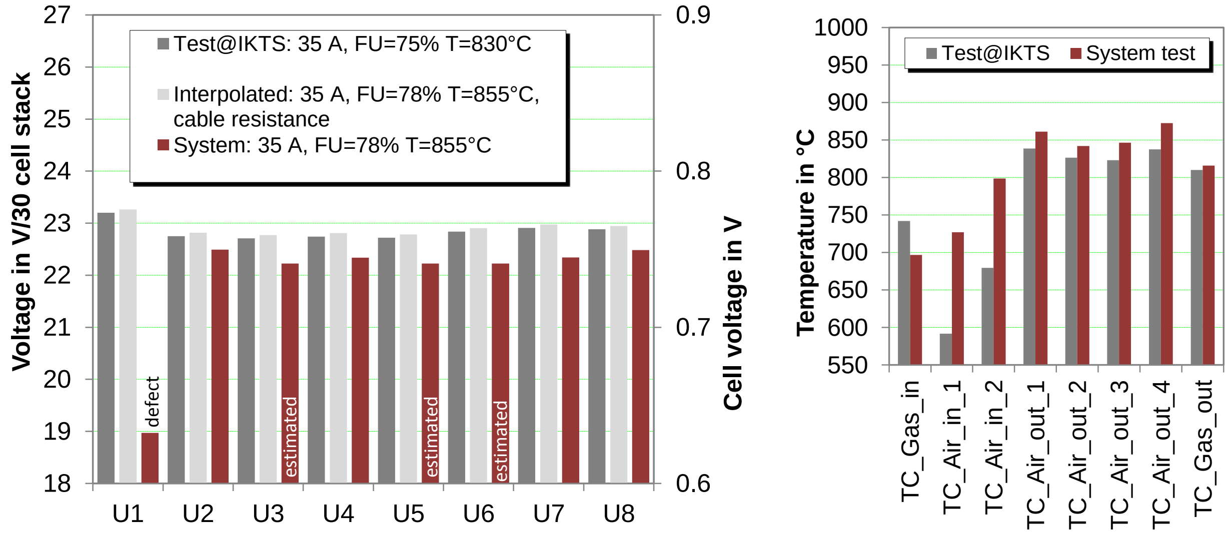


Figure 10: Comparison of 8x30-cell MK352 stack module performance with woodchip reformate between test rig and system operation at 35 A, air at test rig: 704 Nl/min, air at system: 460 Nl/min

During the system initialization phase several failures occurred that had some impacts on the performance (i.e. fuel utilization of >90 % or coking of anodes which cleaned by oxidation), which can be the reason for the slightly lower performance at comparable operation conditions. On the other hand there are much more parameters during system operation with higher uncertainty (gas composition, flows, impurities etc..) which lead to fluctuating values.

The power output during system operation at 35 A of 6040 W, leads to an electrical efficiency of $\eta_{el}$=43.1 % ($P_{el}$ , DC load to fuel input related to the NCV of the fuel) and is slightly lower than the test rig operation with 6430 W at $\eta_{el}$=43.6 %. After reaching the power point at 35 A for comparison to test rig operation the current at the system operation was increased to 36 A and the maximum power output was reached with 6372 W, a fuel utilization of 79 % and electrical efficiency of $\eta_{el}$=45.0 %. The high electrical efficiency achieved with the first testing plant shows the advantages of a combined biomass gasifier / SOFC plant and provides promising prospective for the SOFC technology for future $CO_2$ neutral CHP applications.

### Conclusions and outlook

The combination of a biomass gasifier with a SOFC is a promising approach for $CO_2$-neutral energy supply. To achieve a high number of annual operation hours of the SOFC at varying heat demands, a portion of the product gas from the gasifier is led through the gas cleaning unit to the SOFC system while the remaining product gas is combusted in a burner, which is directly coupled with a boiler. This strategy enables to gain a constant high-load electricity production at a high heat production flexibility. Based on this approach the work regarding the single plant components was initialized and the gasifier with an integrated product gas extraction and heating was further developed for significantly enhanced fuel flexibility and a gas with low tar contents. The cleaning of gas extracted from the gasifier to the SOFC has been successfully demonstrated but has to be optimized for durability and compact system integration. The stationary SOFC system tailored to the gas composition of the cleaned and reformed product gas from the gasifier has been developed based on the existing CFY-stack technology. The stack module itself has been slightly modified with respect to easier assembly, safe compression, improved tightness and lower pressure drop. The balance of plant components have been newly developed for the integration into the whole plant concept. Validation tests with the stack module on the test bench have shown that 6430 $W_{el}$ were achieved at 35 A and 75 % fuel utilization and 835°C, similar to the operation of the complete biomass SOFC CHP system achieving 6372 W at 36 A, 79 % fuel utilization and 855 °C. The system efficiency of 45 % (NCV of the slip stream gas from the GCU) even exceeded the targeted value and shows the potential for advanced CHP systems with optimized behaviour of every component.
An optimised CHP testing plant is under development which includes improvements of the SOFC, the gasifier and a more compact and integrated GCU. In the next phase of the project important results with experiments on cell and stack level with the aim to define limits regarding tar, HCl and $H_2S$ contaminants in the gas for stable operation without accelerated degradation shall be generated. The direct tar reforming as well as simplified control algorithms “sensed by the stack” shall also be addressed and pave the way to commercialization.

## 4. Acknowledgements

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# References


[1] Kalt G., 2014: Wirtschaftlichkeit und Potentiale von Holzgas-KWK-Anlagen in der österreichischen Sägeindustrie (in German), 4th Mid-European Biomass Conference, Graz, Austrian Biomass Association (Ed.), Austria (2011)

[2] Obernberger I., Thek G., Reiter D, Economic evaluation of decentralised CHP applications based on biomass combustion and biomass gasification, Proc. of the 3rd Mid-European Biomass Conference, Graz, Austria (2008)

[3] Zeymer M., Herrmann A., Oehmichen K., 2014: Technisch-ökonomisch-ökologische Bewertung von kleintechnischen Biomassevergasern (in German), Proc. of the 4th Mid-European Biomass Conference, Graz, Austria (2014)

[4] Obernberger I., Mandl C., Brandt J., 2016: Demonstration of a New Ultra-Low Emission Pellet and Wood Chip Small-Scale Boiler Technology. 24th Europ. Biomass Conference and Exhib., ISBN 978-88-89407-165, 367-374, Amsterdam, NL (2016)

[5] Aigenbauer S., Schnetzinger R., Höftberger E., Schmidl C., Haslinger W., StirBio: Operation and Efficiency of a Wood-Pellet Fired 5 KWel Stirling. 23rd European Biomass Conference and Exhibition, ISBN 978-88-89407-516, Vienna, Austria (2015)

[6] Brunner T., Ramerstorfer C., Obernberger I., Kerschbaum M., Aravind P.V., Makkus R., Megel S., Hauth M., Seidl M., Weissensteiner S., Götz T., Zappa W.: Development of a highly efficient micro-scale CHP system based on fuel-flexible gasification and SOFC,25th European Biomass Conference and Exhibition, Stockholm, Sweden, ISBN 978-88-89407-17-2, pp. 725-731, (2017)

[7] C. Bienert, M. Brandner, S. Skrabs, A. Venskutonis, L.S. Sigl, S. Megel, W. Beckert, N. Trofimenko, M. Kusnezoff, and A. Michaelis, CFY-Stack Technology: The Next Design, SOFC-XIV: 14th International Symposium on SOFC, Glasgow, UK (2015)

[8] S. Megel, M. Kusnezoff, N. Trofimenko, et.al, High efficiency CFY-stack for high power applications, SOFCXII, ECS Transactions, 35 (1), 269-277 (2011)

[9] A. Venskutonis, M. Brandner, W. Kraussler and L. Sigl, SOFC-XI: 11th International Symposium on SOFC, S.C. Singhal, H. Yokokawa (eds.), 1353-1359, Vienna, (2009)

10] S. Megel, C. Dosch, S. Rothe, M. Kusnezoff, N. Trofimenko, V. Sauchuk, A. Michaelis, C. Bienert, M. Brandner, A. Venskutonis, L. S. Sigl, Progress in design and performance of CFY stacks, 11th CMCEE (Acers) Vancouver, Canada (2015)

[11] C. Folgner, V. Sauchuk, S. Megel, M. Kusnezoff and A. Michaelis, Interconnect Corrosion in Steam Containing Fuel Gas, SOFC-XV: 15th International Symposium on Solid Oxide Fuel Cells, Hollywood, FL, USA (2017)

[12] S. Megel, M. Kusnezoff, W. Beckert, N. Trofimenko, C. Dosch, A. Weder, M. Jahn, A. Michaelis, C. Bienert, M. Brandner, S. Skrabs, W. V. Schulmeyer, L. S. Sigl, CFY-Stacks: Progress in Development, 12th European Fuel Cell Forum, Lucerne, CH A0903 (2016).

[13] M. Brandner, C. Bienert, S. Megel, M. Kusnezoff, N. Trofimenko, V. Sauchuk, A. Venskutonis, W. Kraussler A. Michaelis and L.S. Sigl, Long Term Performance of Stacks with Chromium-based Interconnects (CFY), ECS Transactions, 57 (1) 2235-2244, SOFCXIII, Okinawa, JP (2013)

[14] M. Hauth, J. Rechberger, S. Megel, M. Kusnezoff, Operating Results of the SOFC20 Stationary SOFC CHP System using a CFY-Stack Platform, 11th European Fuel Cell Forum, Lucerne, CH, A1205, (2014)

[15] S. Megel, C. Dosch, S. Rothe, C. Folgner, N. Trofimenko, A. Rost, M. Kusnezoff, E. Reichelt, M. Jahn, A. Michaelis, C. Bienert, M. Brandner, Co-Electrolysis with CFY-Stacks, SOFC-XV: 15th Int. Symposium on SOFC, Hollywood, FL, USA (2017)

[16] M. Seidl, N. Soukup, S. Weissensteiner, C. Sallai, R. Lehner, M. Hauth, Development of a multi fuel SOFC platform for CHP and CCHP applications, 13th European Fuel Cell Forum, Lucerne, CH, A1201, (2018)